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AN EXPERIMENTAL STUDY OF HIGH FRONT-TO-BACK POWER RATIOS OF A SMALL HORN ANTENNA IN THE NOSE OF A 5"-38 PROJECTILE

11 August 1952

U. S. NAVAL ORDNANCE LABORATOF

WHITE OAK, MARYLAI

AN EXPERIMENTAL STUDY OF HIGH FRONT-
TO-BACK POWER RATIOS OF A SMALL HORN ANTENNA
IN THE NOSE OF A 5"-38 PROJECTILE

Prepared by:

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ABSTRACT: An experimental investigation initiated to determine the front-to-back power ratio characteristics at X-band (3cm) frequencies of a horn receiving antenna mounted in the nose of a 5"-38 projectile is described. It was discovered that the front-to-back ratio increased appreciably upon optimizing variable parameters of the antenna system. These variable parameters are associated with the internal configuration of the front case and with the antenna structure and position. Front-to-back ratios of greater than 54 decibels were obtained. Fluctuations of the power ratio with respect to illumination angle (i.e., the angle between the longitudinal axis of the projectile and the line of sight), however, would appear to preclude practical utilization of much of this increased front-to-back ratio.

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The investigation described in this Report was carried out as a pre-
liminary feasibility study of the maximum front-to-back power ratio
obtainable with a microwave antenna system mounted in the nose of a
small projectile.

References are made in the text to the following publications:

(a)   "Theory of the Electromagnetic Horn", W. L. Barrow and L. J. Chu,
      Proc. I.R.E., 27, 51-64, (1939)
(b)   "Diffraction Theory of Electromagnetic Waves" J. A. Stratton and
      L. J. Chu, Phys. Rev. 56, 92-112 (1939)
(c)   "Elektromagnetische Theorie der Beugung an Schwarzen Schirmen",
      Kottler, F., Annalen der Physik, 71, 457-508 (1923)
(d)   "Calculation of the Radiation Properties of Hollow Pipes and Horns"
      L. J. Chu, J. Appl. Physics, 11, 603-610, (1940)
(e)   "Equivalence Theorems of Electromagnetics" Schelkunoff, S. A.,
      B.S.T.J. 15, 92-112, 1936
(f)   "The Theory of the Radiation Patterns of Electromagnetic Horns",
      Horton, C. W., Defense Research Lab., U. of Texas Contract NOrd-9195,
      May 1948
(g)   "Rectangular Hollow-Pipe Radiators" W. L. Barrow and F. M. Greene,
      Proc. I.R.E. 26, 1498-1519, (1938)

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AN EXPERIMENTAL STUDY OF HIGH FRONT-
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IN THE NOSE OF A 5"-38 PROJECTILE

INTRODUCTION

1. Several independent studies of the theory of the radiation patterns
of electromagnetic horns have been made. In reference (a), Barrow and
Chu derived the general radiation formula from the Kirchhoff formula for
vector fields. The radiation formula was modified by Stratton and Chu
(reference (b)) by the application of Kottler's formulas (reference (c))
in which electric charges are introduced so that the assumed field satisfies
Maxwell's equations. As Chu points out in reference (d), the accuracy
of the modified radiation formula depends upon how closely the assumed
field approximates the actual field over the surface of integration.
Horton in reference (f) has extended Schelkunoff's equivalence theorems of
reference (e) on electromagnetic fields to an analytic analysis of the
radiation patterns produced by different modes of vibration in various
wave guides. The formulas developed by Horton for the theoretical
radiation pattern of a circular horn are equivalent to those developed
by Chu for radiation from the open end of a hollow pipe. Contrary to the
indications of the formulas, experimental results given in reference (g)
show the presence of a rear lobe. Reference (g) attributes this to diffrac-
tion around the edges of the radiator.

2. All the radiation formulas mentioned above assume a plane wave front
at the mouth of the radiator. This assumption is not correct in the case
of a flared horn, as indicated in reference (f). Therefore, the accuracy
of these theoretical methods depends upon the proper choice of boundary
conditions at the mouth of the horn. The patterns calculated by Horton
show power nulls at several positions. The patterns also indicate that
as the aperture diameter is increased the beam width becomes smaller,
and the number of side lobes increases. Again experimental evidence
indicates the presence of nulls, which are not as sharp as the calculated
values. In addition to the reasons mentioned above for the discrepancies
between the calculated and experimental patterns, it should be noted that
the effect of induced surface currents is neglected in the derivation
of these formulas. Experimental evidence indicates the magnitude of these
surface currents is small.

3. The experiments described in this Report were conducted in order to
investigate methods of obtaining the maximum front-to-back power ratio of
a small horn antenna housed in the nose of a projectile. A mathematical
computation of the characteristics of such a configuration would be
extremely difficult due to the existence of complex boundary conditions.
Therefore, an experimental approach was used throughout this investigation.

4. A study of the characteristics of horn antennas indicated that the
front-to-back ratio of a small receiving horn antenna mounted inside a

projectile might be substantially improved by two methods. First, the surface currents on the case of the projectile might be attenuated. Second, very small reflectors might be located in front of the horn to reflect energy of the proper phase and amplitude into the horn to cancel the back-radiation due to diffraction.

5. Aerodynamic considerations limited the extent of possible external alterations to the projectile and front case. Variable parameters at our disposal were thus limited mostly to internal variations. Examples of these parameters are: thickness of plastic front case, shape of internal front case surface, longitudinal placement of horn, extent and shape of metallic front case insert, and dielectric constant of the plastic. Extensive alterations of the front case were limited by the expense and length of time involved in any mold revision.

DESCRIPTION OF EQUIPMENT

6. A block diagram of the equipment used in this study is shown in Figure 1. The 2K39 klystron oscillator, immersed in a constant temperature oil bath for stabilization, was frequency modulated with a 20 kc/sec. signal. The power output of the klystron was fed through a calibrated 20 decibel flap attenuator, and a precision variable attenuator, to a pyramidal transmitting horn antenna of approximately 12° beam width. Figure 2 illustrates the method of mounting the projectile. The projectile was supported by a 1.5 inch diameter polystyrene rod. In order to reduce stray reflections from objects in the vicinity, the projectile axis was tilted 11°. The transmitting antenna, located a distance of 190 inches from the projectile, was aligned accordingly. The conical receiving horn and crystal holder assembly, located inside the projectile, are illustrated in Figure 3. The crystal output (Figure 1) was fed to the input of a low-frequency regenerative receiver. The output of this receiver was measured by a voltmeter.

7. Initial experimental equipment utilizing a CW klystron signal and a chopper type DC amplifier was replaced to minimize amplifier instability and noise level variations. It was also discovered in the initial stages that reflections from distant objects gave erroneous data if the transmitting and receiving antennas were aligned horizontally.

8. The method used to determine front-to-back power ratio was as follows: with the rear of the projectile directly illuminated, attenuation was removed until a given reference level was obtained on the voltmeter. The projectile was then rotated 180° and aligned so that the front case was directly illuminated. Sufficient attenuation was then added until the same voltage reference level was obtained. The difference in attenuation was thus a measure of the front-to-back ratio of the projectile antenna system. This eliminated any error due to the nonlinearity of the crystal detector, receiver, or vacuum tube voltmeter, leaving only the calibration error of the attenuators. Sufficient energy was available to enable the measurement of front-to-back ratios of about 57 decibels.

EXPERIMENTAL RESULTS

A. Results of Initial Tests on Simulated Projectile.

9. During the initial phases of experimentation a 4-1/2 inch outside
diameter aluminum cylinder was used as a simulated projectile (Figure 4).
The rear of this cylinder was sealed with a metal plate, and a brass insert
was secured in the front of the cylinder. The plastic front case was then
screwed onto this insert. Initial tests with a pyramidal horn mounted
inside the cylinder, and with a layer of Harp microwave absorbent material
wrapped about the circumference of the cylinder, indicated a front-to-back
ratio of about 45 decibels. With the addition of the plastic front case
and a quarter wave slotted ring choke on the cylinder body, a ratio of about
52 decibels was obtained. The plastic front case used in this section of
the experiment was a GASR plastic rocket nose molded from Dow's polystyrene
666 in NOL mold number D-392.

10. As the results of the initial tests showed promise a more refined
antenna system was designed. A conical horn was constructed (Figure 3)
and mounted, with nonconducting support, in the cylinder. It was noted that
an axial displacement of the horn would cause variations of the power ratio.
Using the quarter wave ring choke (Figure 4) and placing the horn in the
optimum axial position, a front-to-back ratio of 56 decibels was obtained,
without aid of the absorbent material. An oversize insert (Figure 4) having
an inside diameter of 2.777", was constructed which incorporated the physical
dimensions of the quarter wave ring choke. With this new insert a ratio
of 56 decibels was again obtained without aid of absorbent material. Using
this configuration the changes of power ratio with small deviations of
illumination angle were investigated. The illumination angle is defined as
the angle between the longitudinal axis of the projectile and the line of
sight. Positive illumination angles are assumed when the angle between
the longitudinal projectile axis and the horizontal plane is less than
the line of sight angle. Thus if the gun and radar were at the same point
only positive illumination angles would be obtained. The extent of these
changes of front-to-back power ratio vs. illumination angle is indicated
in Figure 5.

11. Tests were also made to indicate the effect on front-to-back ratio of
the variation of horn flare angle and aperture. From the results of these
tests and from the consideration of space limitation in the front case a
flare angle of 14.3° and an aperture of 2-1/4 inches were selected as the
optimum horn dimensions. Various other experiments were devised to show
the effect of the variation of other parameters. In brief, those con-
sisted of the application of microwave absorbents (polyiron, aquadag, etc.)
to various portions of the cylinder and front case surfaces, variations of
insert inside diameter, and the use of conical horns with flared edges.
Few of these tests resulted in more than 2 or 3 decibels increase of
front-to-back ratio, indicating that the magnitude of the surface waves
on the projectile body was small. The most significant of the miscellaneous

tests was the use of a horn modified by the addition of a quarter wave choke on the edge (Figure 4). The quarter wave choke increased the front-to-back ratio several decibels. Increasing the insert inside diameter increased the front-to-back ratio slightly. This, together with data taken with different aperture horns, indicated that, for any given aperture, the front-to-back ratio is a function of the coupling between horn and insert (Figure 5).

B. Results of Tests on a 5"-38 Projectile

12. Tests with the simulated projectile yielded data which indicated that an increase of about twenty decibels in the front-to-back power ratio of an electromagnetic horn antenna might be obtained by mounting the horn inside a projectile. Thus it was decided to investigate the characteristics of a conical horn antenna mounted in an actual 5"-38 projectile. This projectile was equipped with an XV-46 VT fuze plastic front case (NOL Sk., No. 194325 was used in molding this front case from Dow's polystyrene 666). This projectile was first modified, to reduce weight, by decreasing the wall thickness keeping the outside diameter constant. In addition, a threaded rear plate was machined to provide access to the shell interior while maintaining the original exterior dimensions. The horn positioning mechanism (Figure 6) was designed to facilitate accurate longitudinal positioning of the horn.

13. The first tests with this projectile demonstrated that the front-to-back power ratio, using an antenna electrically insulated from the projectile, was five decibels greater than in the case of an uninsulated antenna. In all subsequent tests data were collected using the insulated horn antenna.

14. Experiments with this configuration again showed a dependence of front-to-back power ratio upon longitudinal horn position. In addition to this effect it was discovered that the power ratio varied as the front case was extended from the projectile by unscrewing (See Figure 7). A detailed investigation of the dependence of power ratio on these two variables was conducted. The extent and effect of these variations may be noted in Figures 8 and 9.

15. It was thought that the irregularities shown in these curves were due to multiple reflecting sources within the front case. Thus an all plastic polystyrene front case was molded in an attempt to eliminate at least one of these reflecting sources, i.e. the boundary between metal insert and plastic. With this all plastic front case, curves indicating a more regular variation of front-to-back power ratio were obtained which appeared to have a periodic nature, as shown in Figure 10. Figure 11 shows the dependence of front-to-back power ratio upon longitudinal horn placement using the all plastic front case.

16. The existence of an apparent periodic condition within the front case was further experimentally substantiated by positioning small metal reflecting

rods (0.1" diameter by 1/2" long) on the front case surface. Several critical positions, rather regularly spaced, were found where energy was reflected in the proper phase and amplitude relations to create a maximum of front-to-back power ratio. In addition to the use of these rods to demonstrate the effect of reflection, the front case was sliced and a copper ring inserted between the two sections. Again the optimum placement of this ring resulted in a maximum front-to-back power ratio. The plastic nose was filed away slightly to secure optimum placement of the ring. The presence of an apparent lack of symmetry was demonstrated when a semicircular metallic ring was substituted for the complete ring. The lack of symmetry, as seen also in curves of front-to-back ratio versus illumination angle, was possibly due to the effect of the polystyrene projectile support.

17. Miscellaneous tests conducted with the horn antenna mounted in the projectile included a check of the effect of microwave absorbent layers on the body, use of an integral-horn and insert (Figure 4), and the use of spacers to vary the projectile length. Absorbent layers of Harp material wrapped about the circumference of the projectile increased the front-to-back ratio slightly. The integral horn and insert gave a lower power ratio than that of the isolated horn. Increasing the length of the projectile by the insertion of a metallic spacer at the rear showed a slight dependence of front-to-back power ratio on length. As no significant increase of front-to-back ratio resulted from small alterations of length, this section of the experiment was not investigated further. These tests all indicate that the effect of surface waves is small. Due to the small inside diameters of the projectile and front case, little variation of horn aperture without a large decrease in gain was possible. The optimum horn aperture used throughout this section of the experiment was 1-15/16" diameter.

18. In addition to the tests already enumerated, rather extensive checks of the variation of front-to-back ratio with changes of illumination angle were made. Figures 12 and 13 are representative samples of the results. These curves indicate that a front-to-back ratio of better than 40 decibels can be achieved over a range of illumination angles of ± 6°. A ratio of about 48 decibels might be achieved over a range of ± 2°. This represents a possible increase in front-to-back ratio of about 8 decibels with a ± 6° illumination angle or about 16 decibels with a ± 2° illumination angle over an isolated horn. During the investigation described in this report the experimental front-to-back power ratio of a particular isolated electromagnetic horn antenna was found to be approximately 32 decibels.

19. It will be noted from Figure 13 that data were also obtained which indicated that the front-to-back ratio was, to some extent, frequency dependent. Variation of illumination angles was measured in the E-plane, positive angles refer to a lowering of the nose with the rear of the projectile illuminated. A complete H-plane antenna pattern is included in Figure 14, from which it is seen that the beam width of the antenna system for this experiment was 91°.

CONCLUSIONS

20. Data have been presented in this Report to indicate that a small horn antenna may be mounted in a projectile so that the antenna system will have a front-to-back power ratio of greater than 50 decibels. This is an increase of at least 18 decibels over the front-to-back ratio of the same horn antenna in free space.

21. This large increase of front-to-back ratio was experimentally obtained by altering the internal relations of the projectile front case and horn antenna. These alterations resulted in the reflection of energy incident upon the front case in the proper phase and amplitude relations to cancel out the back-radiation due to diffraction. It may thus be surmised that with longitudinal movement of the horn the amplitude of the wave front presented to the horn aperture, which results from a combination of diffracted wave and reflected wave from the front case tip, has changed. In extending the front case, the gap between the projectile and metal insert, essentially served to alter both the magnitude and phase of the surface currents entering the front case. Therefore, the quarter wave slotted ring on the simulated projectile functioned more to alter the phase than to attenuate the induced surface currents. These premises are borne out to some extent by the curves obtained using the all plastic front case which indicate an apparent periodicity. Deviations from this periodicity are probably due to edge effects presented to the horn by the edge of the front case. Examples of this deviation occur, for instance, in Figure 10 when the front case is extended to the limit.

22. The adjustment of the variable parameters was extremely critical. Variations of nose extension of the order of magnitude of one thousandth of an inch were sufficient to decrease the front-to-back ratio several decibels. That this should be true follows from the phenomenon assumed to cause the increase of front-to-back ratio.

23. It has also been demonstrated that external reflectors might be positioned on or near the front case surface to accomplish a similar increase of front-to-back power ratio. However, due to aerodynamic considerations, the improvements achieved by reflectors on the surface, and by the use of microwave absorbents on the projectile circumference, have no significance.

24. It has been shown in this experiment that the maximum front-to-back ratio obtainable does not remain constant for small variations of the illumination angle, but drops off rapidly for small deviations from zero degrees. Also, this ratio, for any illumination angle, appears to have some dependence upon frequency. These facts appear to make most suggestions for immediate applications impracticable. It should be pointed out, however, that higher maximum ratios were obtained with the simulated projectile which used larger diameter horns. In fact, ratios of not less than 47 decibels were attained over a range of illumination angles of $-4.2°$ to $+5.8°$ with this simulated projectile.

25. A theoretical study of the mechanism causing this increase of front-to-back ratio, based upon these experimental findings, might prove profitable for application other than the adaptation to projectiles which motivated this investigation.
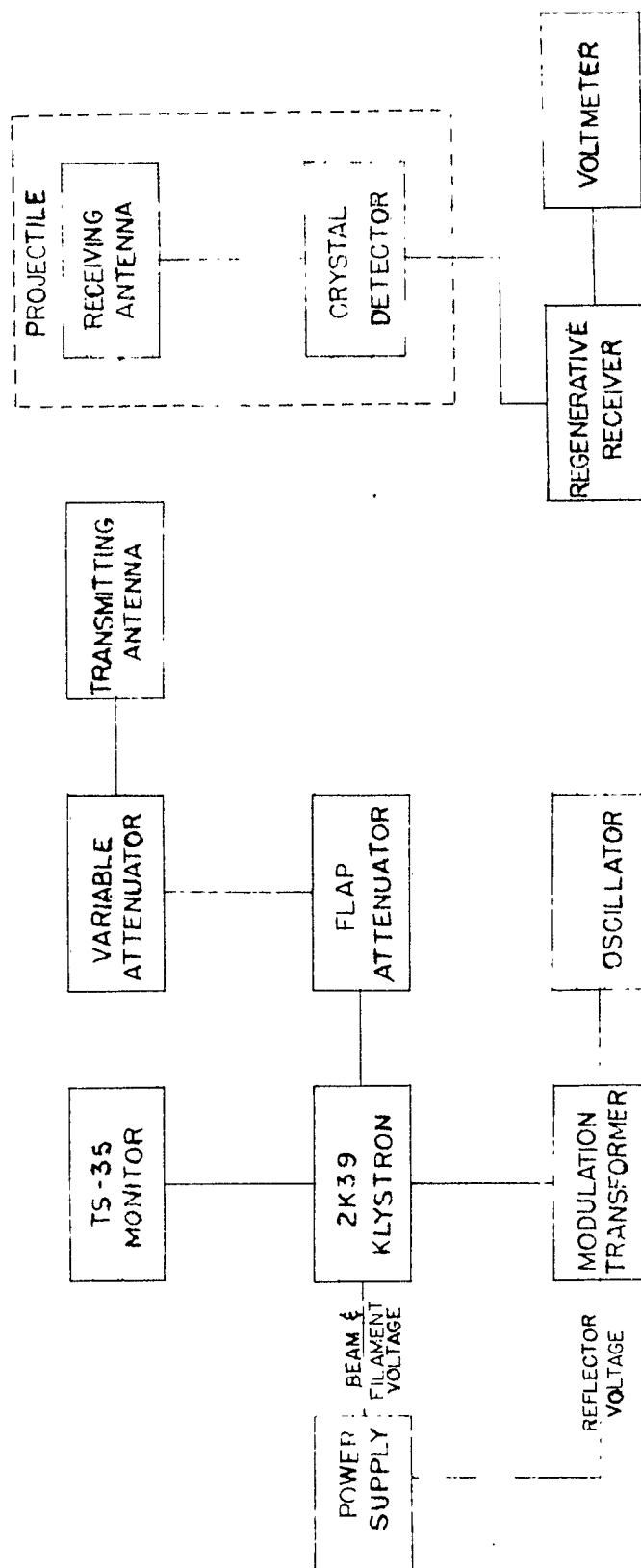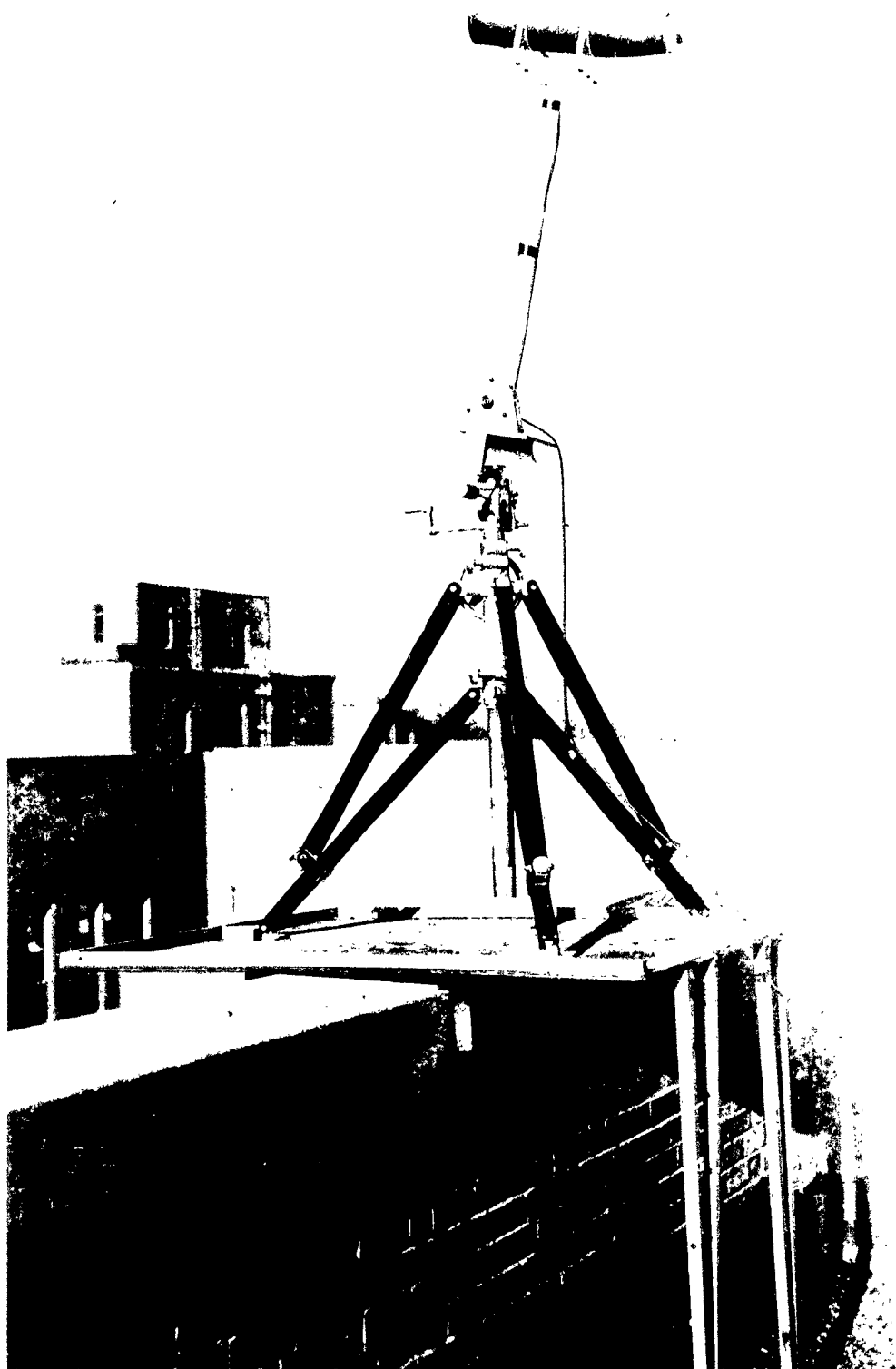
FIGURE 1
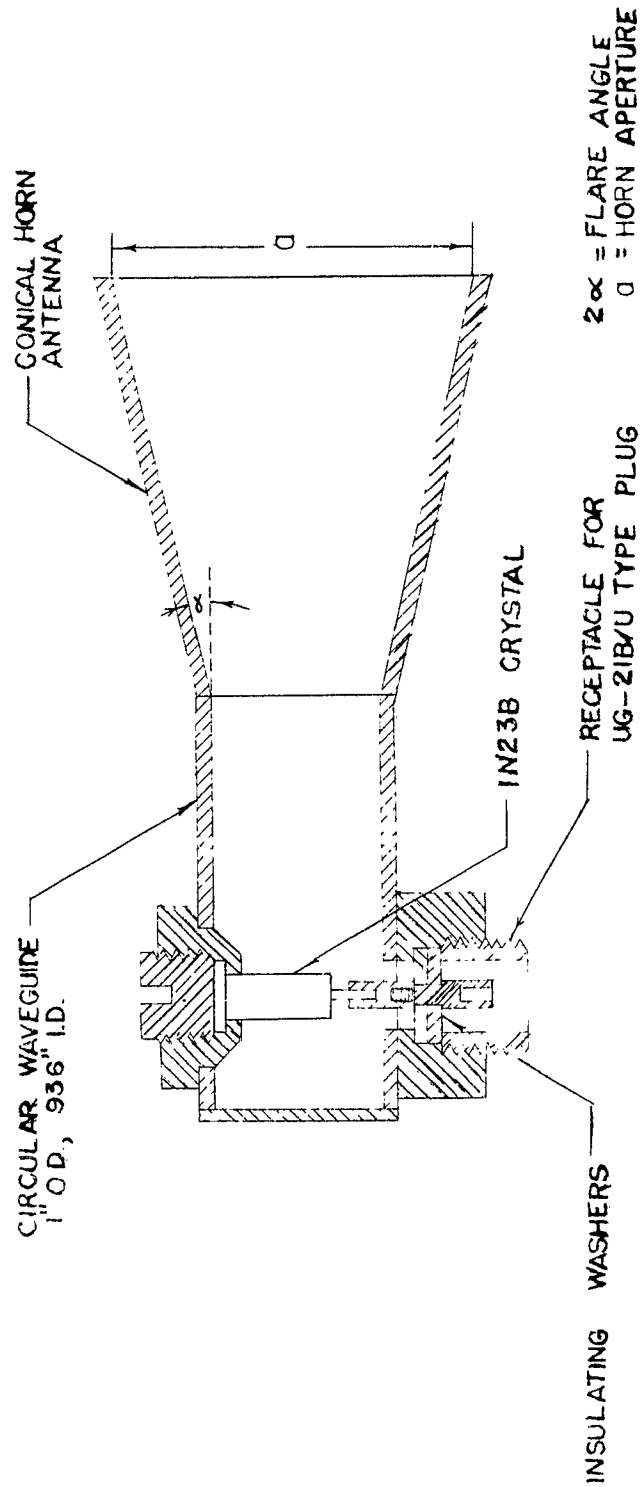BLOCK DIAGRAM OF EXPERIMENTAL EQUIPMENT

FIGURE 2
VIEW OF PROJECTILE MOUNTING

CONFIDENTIAL

FIGURE 3
CONICAL HORN AND CRYSTAL HOLDER ASSEMBLY

OVERSIZE INSERT WITH $\lambda/4$
CHOKE FOR SIMULATED PRO-
JECTILE.

$\lambda/4$ ...
... ... CHOKE ...

SIMULATED PROJECTILE

FRONT CASE WITH ALL PLASTIC
METAL INSERT FRONT CASE

FRONT CASE
INSERT

CONICAL HORN ... NETWORK ...
$\lambda/4$ CHOKE OR HORN AND INSERT

CONICAL HORN ANTENNA
AND HORN POSITIONING
MECHANISM.

FIGURE 4
DISASSEMBLED COMPONENTS OF
... ANTENNA SYSTEM
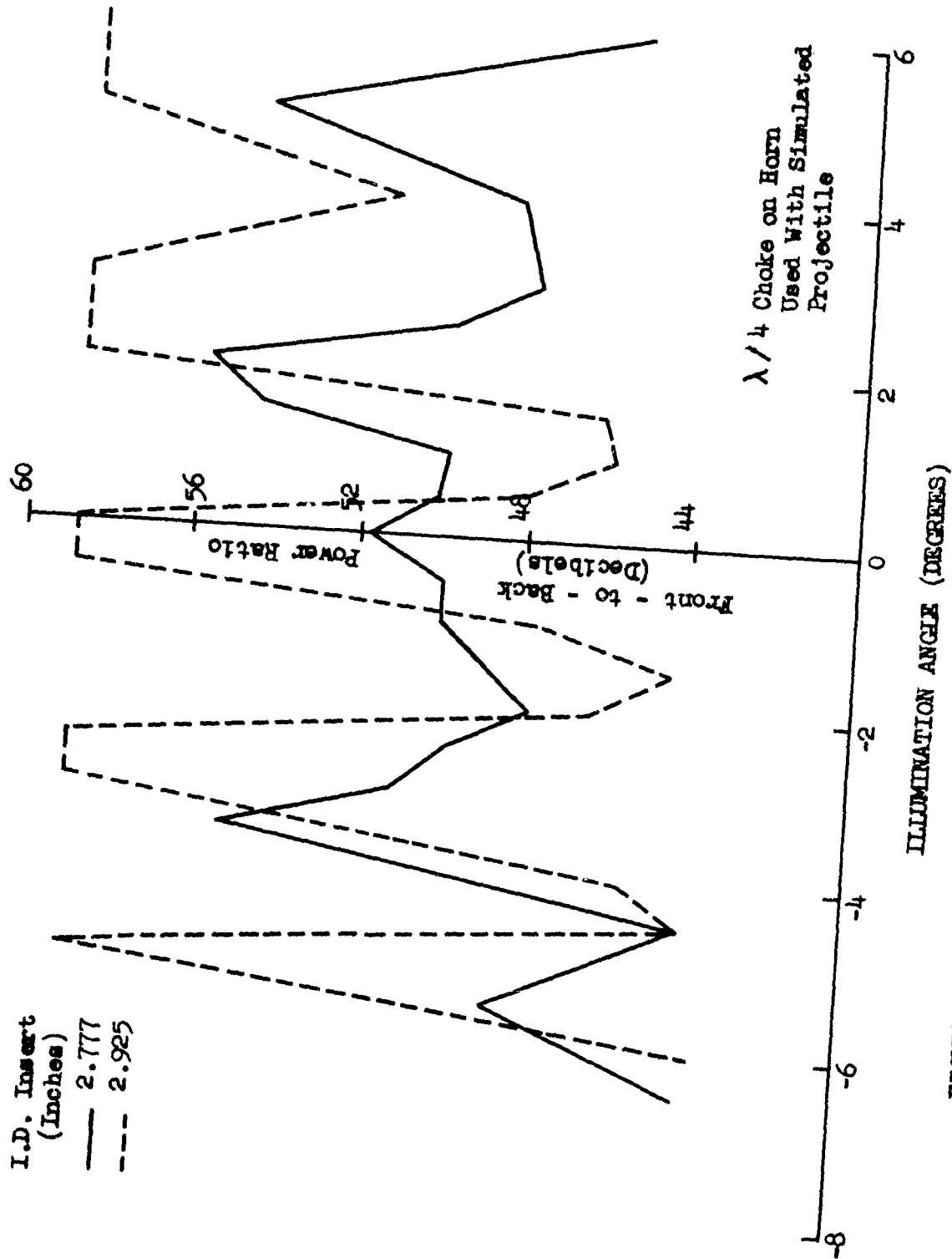
FIGURE 5 - FRONT - to - BACK RATIO vs. ILLUMINATION ANGLE FOR SIMULATED PROJECTILE
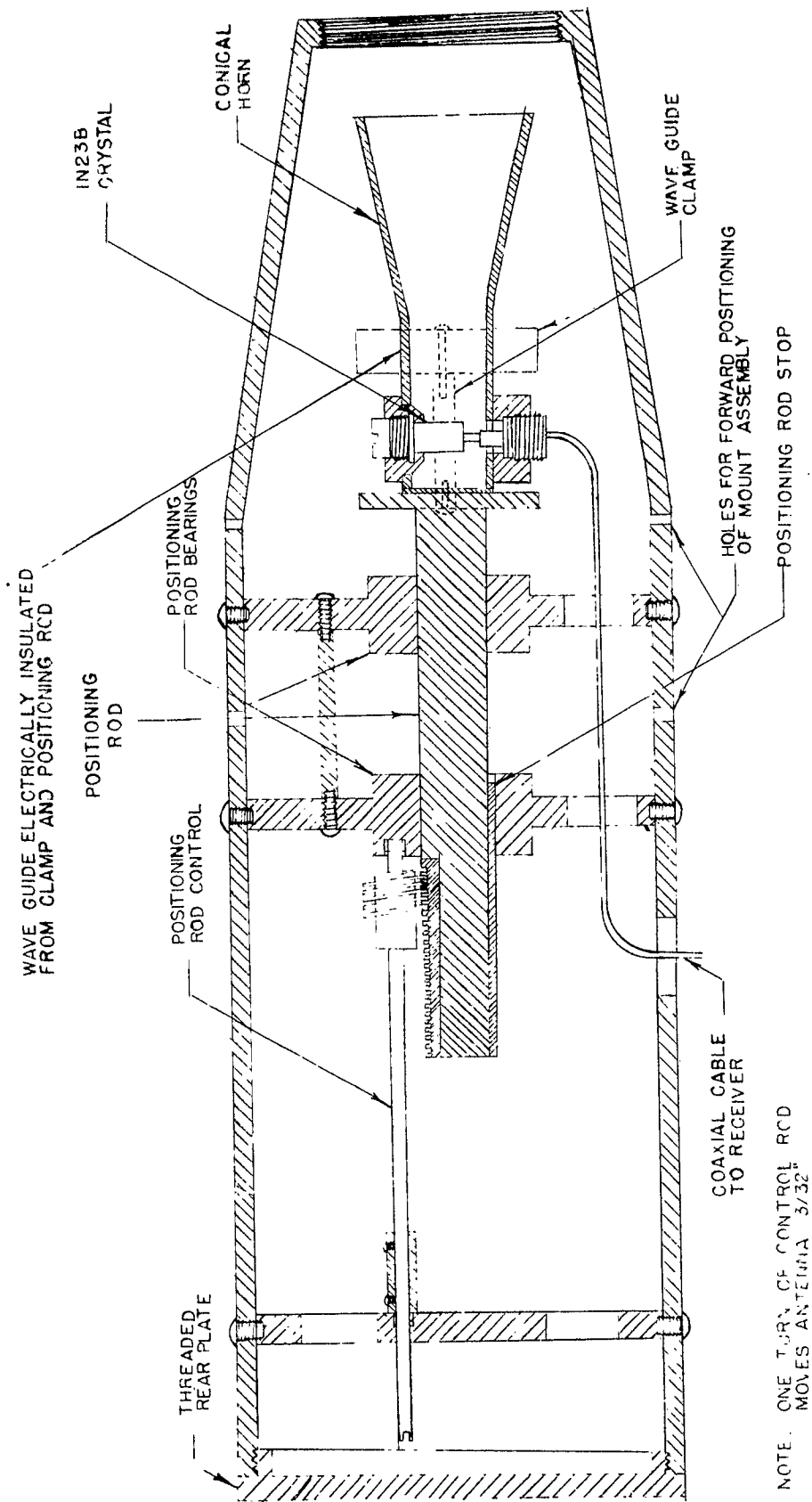
FIGURE 6
HORN POSITIONING MECHANISM IN PROJECTILE
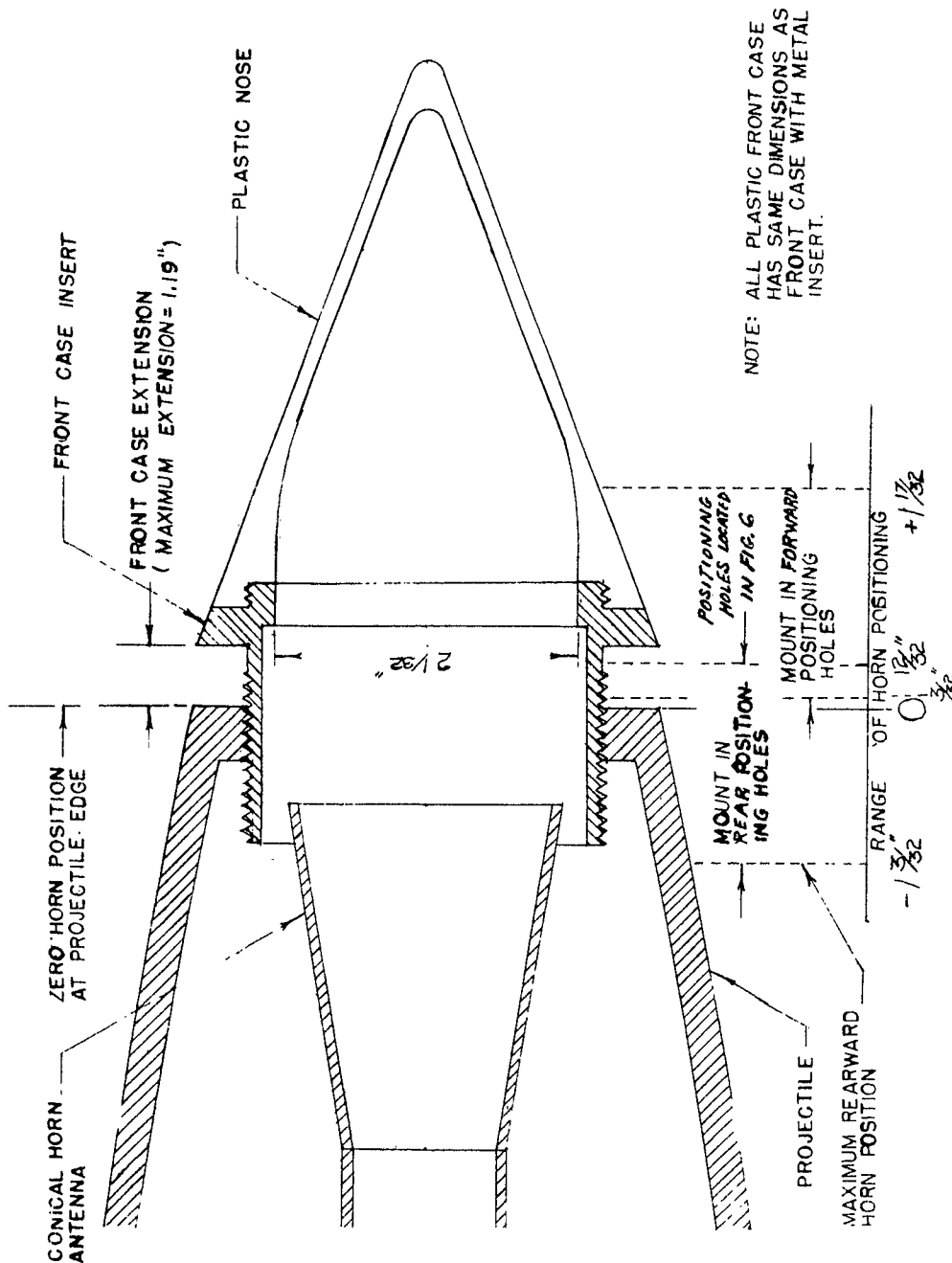
FIGURE 7
FRONT CASE EXTENSION AND HORN POSITIONING
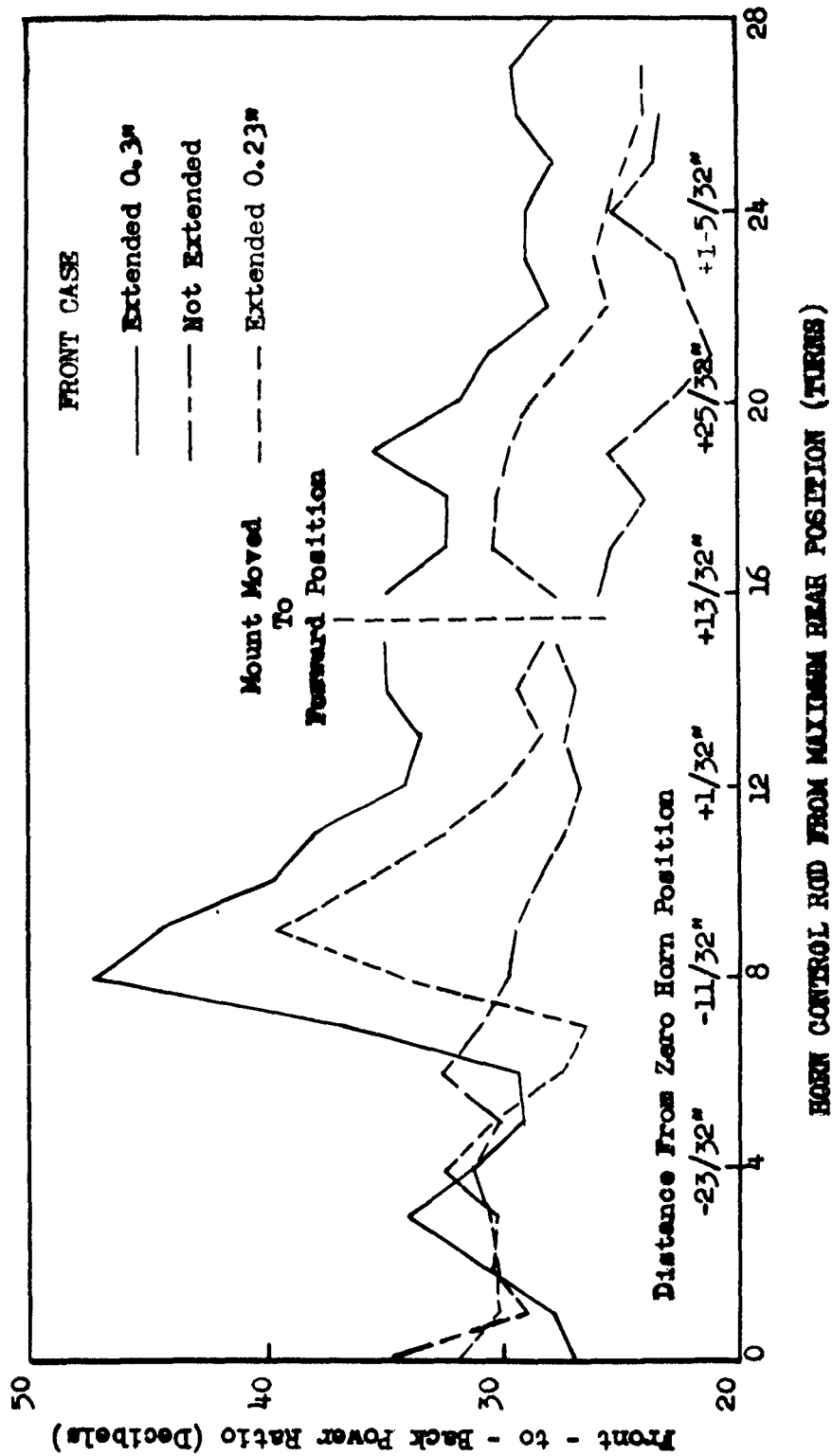
FIGURE 8 - VARIATION OF FRONT - to - BACK RATIO vs. LONGITUDINAL HORN POSITION
(PROJECTILE WITH FRONT CASE AND METAL INSERT)
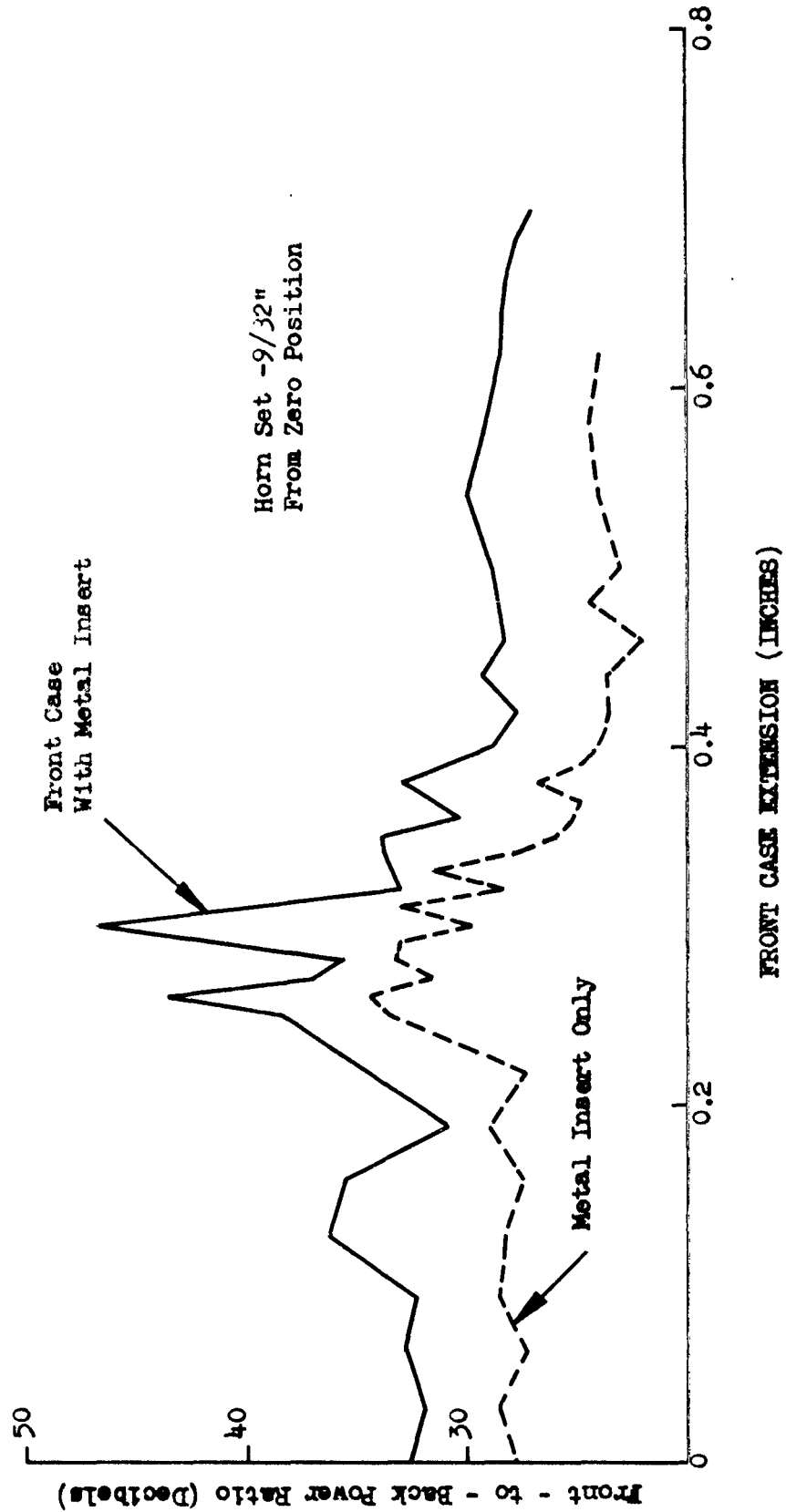
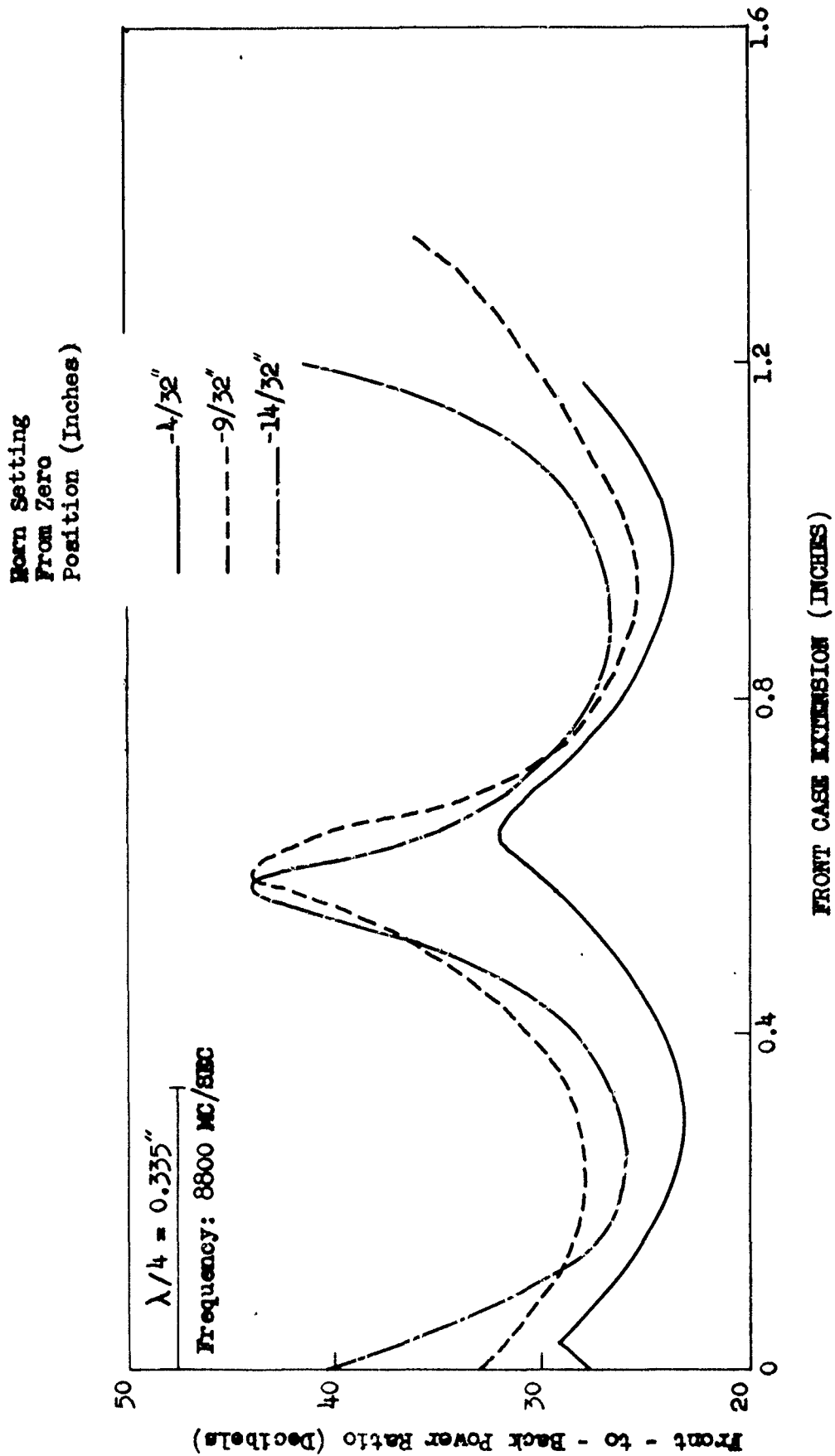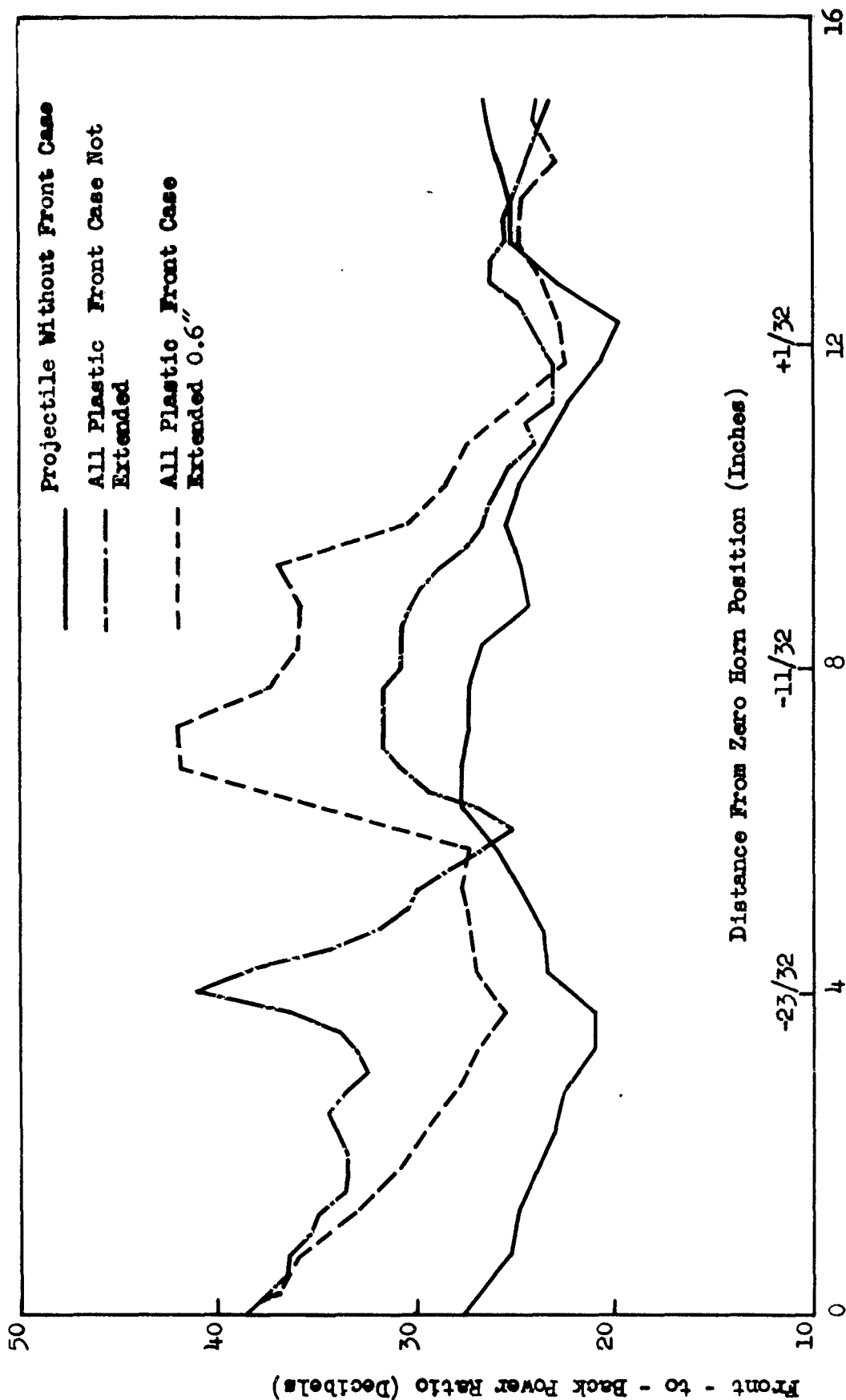FIGURE 9 - VARIATION OF FRONT - to - BACK RATIO vs. FRONT CASE EXTENSION

FIGURE 10 - VARIATION OF FRONT - to - BACK RATIO vs. FRONT CASE EXTENSION (ALL PLASTIC CASE)

FIGURE 11 - VARIATION OF FRONT - to - BACK RATIO vs. LONGITUDINAL HORN POSITION
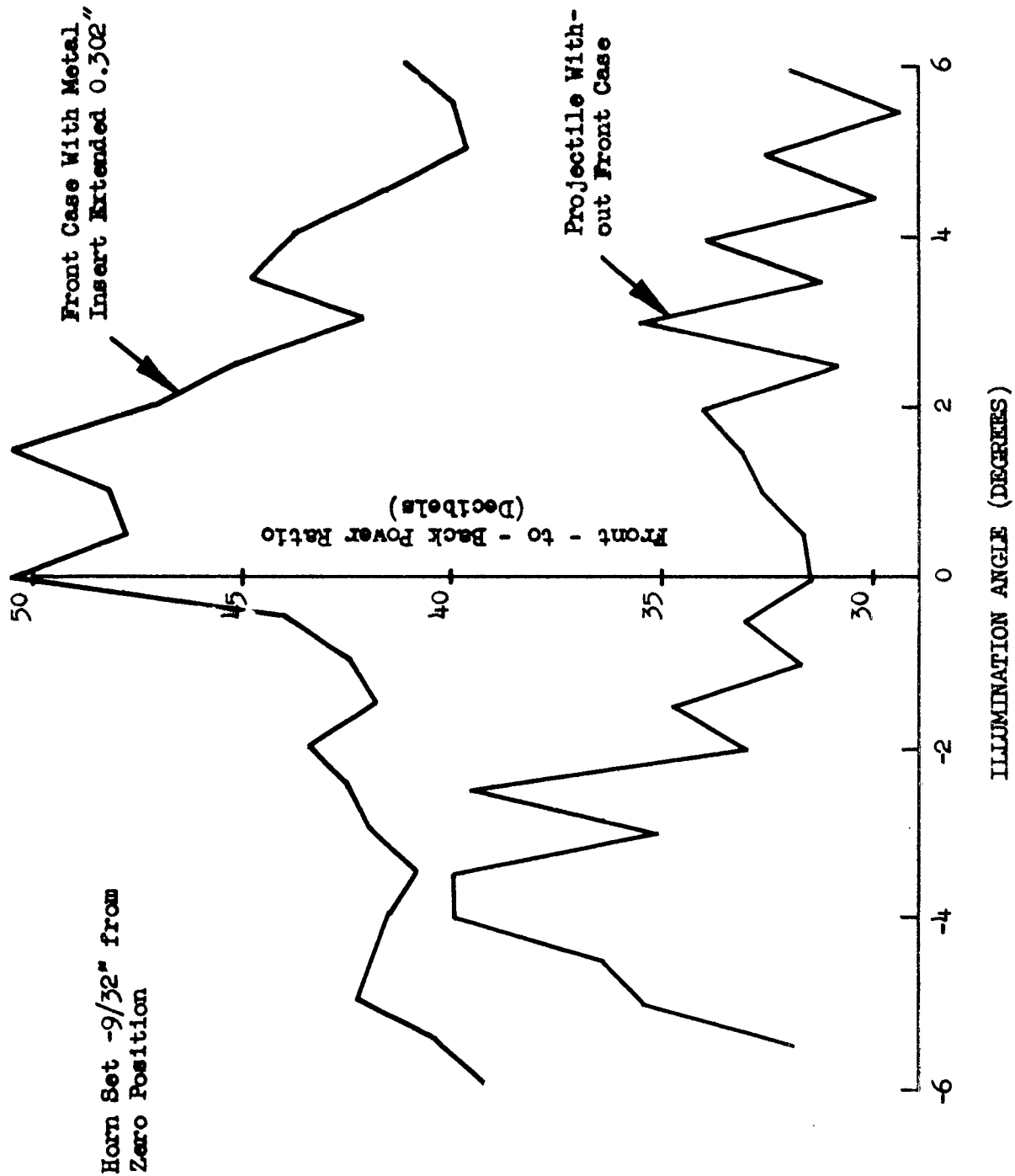
FIGURE 12 - FRONT - to - BACK POWER RATIO vs. ILLUMINATION
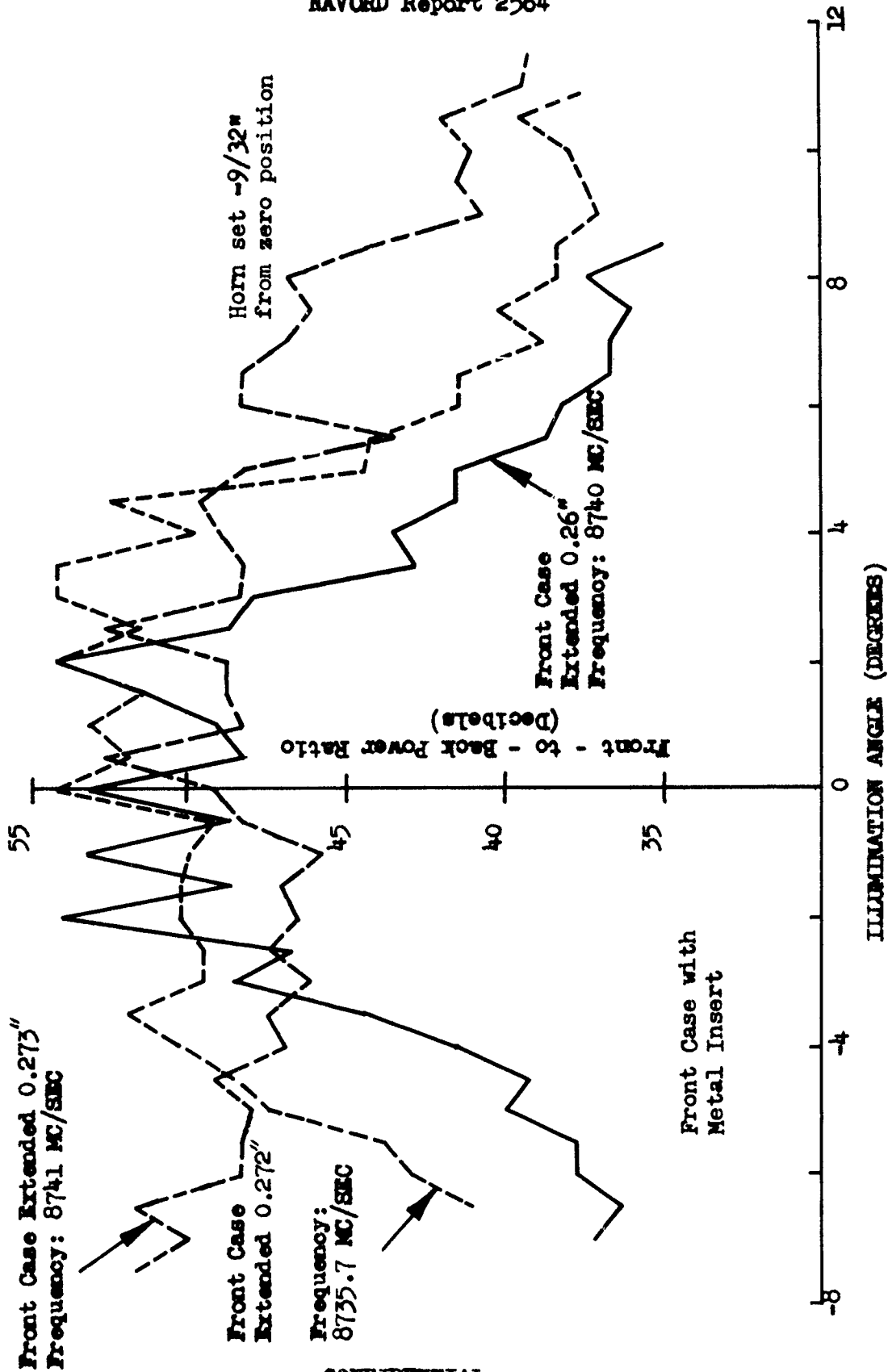ANGLE FOR 5"/38 PROJECTILE

FIGURE 13 - FRONT - to - BACK POWER RATIO vs. ILLUMINATION ANGLE FOR VARIOUS FREQUENCIES

Decibel Scale Denotes Relative
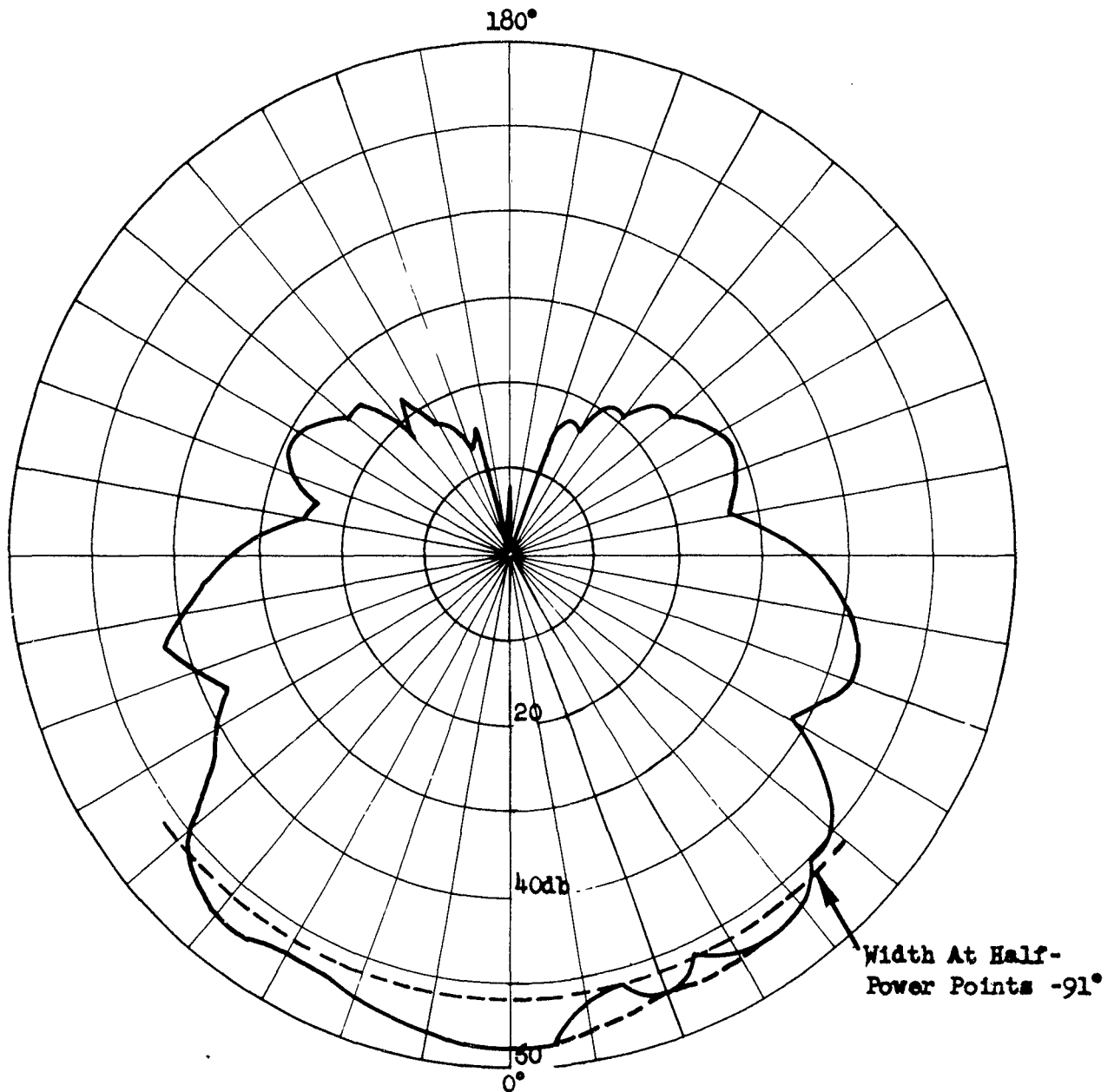Power Levels.

Front Case With Metal Insert
Horn Set-9/32" from Zero
Position

FIGURE 14 - H-PLANE ANTENNA PATTERN